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著者	渡辺 和雄
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Design of a Resistive Insert for a 45 T Hybrid Magnet

T. Asano, Y. Sakai, S. Matsumoto, T. Kiyoshi, H. Yoshioka, K. Takahashi, S. Awaji, and K. Watanabe

***Abstract*—The Tsukuba Magnet Laboratory (TML) and the High Field Laboratory for Superconducting Materials collaborated on the design study of a 50 T-class hybrid magnet. The highest fields of the hybrid magnet were examined with the existing 15 MW DC source at the TML used for the resistive insert magnet. The strength of the Cu-Ag wire exceeds 1400 MPa in ultimate tensile strength (UTS). Several upper-design stresses corresponding to the Cu-Ag wire strength were placed on Bitter disks to evaluate the resistive insert. The design was conducted with two inner radii, 29 mm and 19 mm. Resistive insert magnets are consist of three-layered coaxial Bitter coils operated with the 20 T outer superconducting magnet with a room temperature bore of ϕ400 mm. In this hybrid magnet, a UTS of 1200 MPa is needed for the Bitter disks of the resistive insert to generate 46 T.**

***Index Terms*—Bitter coil, high field magnet, hybrid magnet, resistive insert magnet.**

I. INTRODUCTION

THE hybrid magnet of the Tsukuba Magnet Laboratory (TML) provides magnetic fields of 14.02 T by a superconducting outsert magnet in the 400 mm room-temperature bore (RT bore) and fields of 23.86 T by a water-cooled resistive insert magnet excited by the 15 MW DC power source. In total, it continuously generates a magnetic field of 37.9 T at maximum operation [1].

Collaborative research for the development of a 50 T-class hybrid magnet consisting of a 22 T superconducting outsert is being carried out at TML and the High Field Laboratory for Superconducting Materials (HFLSM) for constructing a next- generation hybrid magnet. In HFLSM, high-strength strand cables were studied for the superconducting magnet (SM). Using these cables, a 20 T 400 mm RT bore superconducting magnet consisting of five layers of $\mathrm{CuNb/Nb_3Sn}$ coils and two layers of NbTi coils was designed [2]. A new candidate material for the resistive insert emerged as a result of Sakai's study of Cu-Ag alloy wires [3]. The Cu-6wt%Ag wire drawn with intermediate annealing exhibited high strength exceeding 1400 MPa with good conductivity exceeding 76% IACS. We initiated trial design of the resistive insert, assuming several stages of strength and conductivity expected from this new wire, for the hybrid magnet composed of the 20 T 400 mm RT bore SM.

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T. Asano, Y. Sakai, S. Matsumoto, T. Kiyoshi, and H. Yoshioka are with the Tsukuba Magnet Laboratory, National Institute for Materials Science, Sakura 3-13, Tsukuba, Ibaraki 305-0003, Japan (e-mail: ASANO.Toshihisa@nims.go.jp).

K. Takahashi, S. Awaji, and K. Watanabe are with the Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan (e-mail: kohki@imr.tohoku.ac.jp).

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II. EVALUATION METHOD AND BACKGROUND

A. Calculation Method

We adopted an axially cooled design for the multi-Bitter resistive insert. Two kinds of copper alloy plates were assumed for the outermost Bitter coil to estimate the performance of the resistive insert. They are Cu-Fe(KFC SH 0.40 mm thickness) and Cu-Cr(OMCL1 SH 0.8 mm thickness). The typical UTS for 88% IACS conductivity of OMCL1 was 440 MPa, and that of KFC was 460 MPa. The tentative Cu alloy plates were assumed for the mid and inner coils of the resistive insert. Tentative maximum design stresses used in the Bitter disk were 700, 780, 830, and 880 MPa, assuming 70% strength of the needed average ultimate tensile strength of the tentative Cu alloy plate for each goal field of the magnet.

In addition, we selected the same radial dimension of the resistive insert as that in a previous report [1] because the diameter of the RT bore in the newly designed SM is also 400 mm [2]. Considering the required center field of the new SM and the electric power circumstance in Japan, we also assume a 20 T 400 mm RT bore. For this reason, the inner diameter of the resistive insert magnet space in the housing was 365 mm, and the outer diameter of the resistive insert magnet installed in this space was 340 mm. The inner diameters of the coil were 38 mm and 58 mm to realize the 32 mm and 52 mm RT bore diameters. Other parameters were defined by the calculations mentioned in a previous paper [1] based on reports by Montgomery [4], Miura [5], and Eyssa [6]. The layout for the cooling holes on the Bitter disk follows that of the Florida Bitter, i.e., a staggered formation [7], [8].

Other restrictions were a 15 MW DC power supply (430 V, 35 kA), cooling water temperature at the magnet inlet (10°C), a 1.6 MPa pressure drop of cooling water between the inlet and outlet, and plate properties for the Bitter disks. The innermost coil of the 32 mm RT bore resistive insert was coaxially divided into two coils.

B. Background for Examination

The maximum magnetic field of the TML 52 mm RT bore HM is 35.5 T [9]. At this magnetic field, the maximum operating stress in the resistive insert is about 66% of the maximum UTS of 942 MPa (at room temperature), and the operating DC power of the WM is 12.8 MW. A revised type of resistive insert succeeding of this is also being prepared in TML using the traditional Cu-Ag alloy plate [10]. The TML HM with this resistive insert will generate 36.4 T at a power of 14.5 MW under a 14.02 T backup field. The specifications are listed in Table I,

TABLE I
PARAMETERS OF THE 52 mm 36 T TML HYBRID INSERT

Coil	A	B	C
Inner radius (mm)	29.0	80.5	127.5
Outer radius (mm)	78.5	126.5	170.0
Height (mm)	233.1	382.0	405.0
Field (T)	11.16	7.62	3.66
Material	Cu-Ag	Cu-Ag	Cu-Fe
UTS (MPa)	942	942	490
%IACS	74	74	88
Stress (MPa)	628	615	275
Power (MW)	4.60	7.32	2.63
Voltage (V)	132.0	284.7	284.7
Current (kA)	34.95	25.65	9.30
Jmax (A/mm2)	442.6	246.0	121.7
Max. temp. (˚C)	98	97	45
Numbers of holes	224	288	240
Tie rods	16	24	24
Disks/turn	8	8	6
	16	16	12
Turns (main)	61	79	155
(end region total)	2	14	2

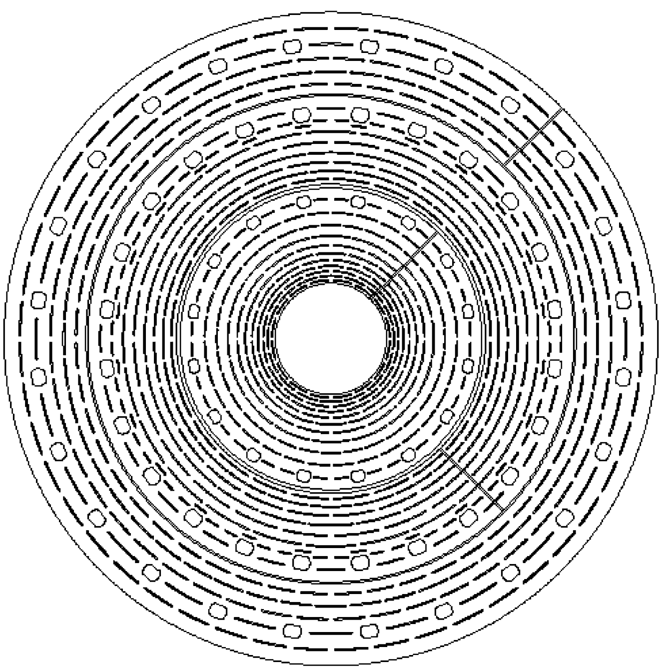

Fig. 1. Bitter disks for the 52 mm hybrid insert. The disks of the outermost coil are made of a Cu-Fe alloy, and those of the other two coils are made of a Cu-Ag alloy. The rectangular tie rod holes used so far in the disks of TML were changed into a circular arc and a parallel plane. The cross section of the tie rod is almost the same as that presented in a previous report [1].

and the Bitter disks and the layout of the coil are depicted in Figs. 1 and 2.

As reported above, the possible adoptive maximum outer diameter for the resistive insert is 340 mm in both the TML SM and the 20 T SM. We evaluated the resistive insert under an additional condition in which the outermost coil was constituted of the same Bitter disks in diameter and layout of the cooling holes presented in Table I and Fig. 1 in order to utilize the existing punching die set to reduce the production costs. The thickness of the Bitter disks used in the coils of the resistive insert was adjusted to obtain a higher magnetic field.

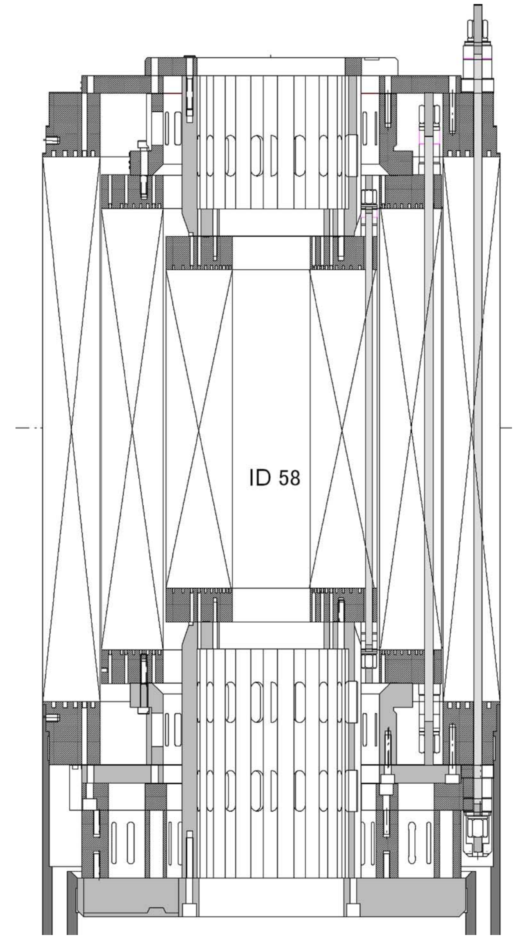

Fig. 2. Coil layout of the new resistive insert being produced for the 52 mm RT bore hybrid insert. The outer diameter is 340 mm. The outer two coils are connected in parallel. The innermost coil is connected in series to these outer two coils. This magnet is built in a pipe with an inner diameter of 365 mm and an outer diameter of 395 mm. This pipe is located in the 400 mm RT bore of the 14.02 T SM outsert currently used at the TML.

III. MAXIMUM FIELD OF THE NEW HM

A. 52 mm RT Bore HM

The calculation results of the attainable magnetic fields in the center of the new HM are plotted in Fig. 3. In this plot, the total magnetic fields of the HM in which the resistive insert is composed of the conventional Cu-Ag Bitter disk correspond to the symbols located at 630 MPa in the upper design stress axis in both types of SM outserts of the TML, i.e., the traditional (14.02 T) and the 45 T plan (20 T).

Increasing the maximum design stress, yields a grater improvement in the total magnetic field under a backup field of the 20 T SM than that of 14.02 T SM, with an operating power of 15 MW. From this calculated result, it is sufficient to achieve the average (rolling direction and its right-angle) UTS of 1000 MPa for the Bitter disk to generate 42 T in the 52 mm RT bore using a 15-MW power source and a 20 T SM of the future plan. A plate with a strength of 1200 MPa UTS in average is needed for the Bitter disk to generate 43.5 T in the 52 mm RT bore in the SM of the 20 T 400 mm RT bore.

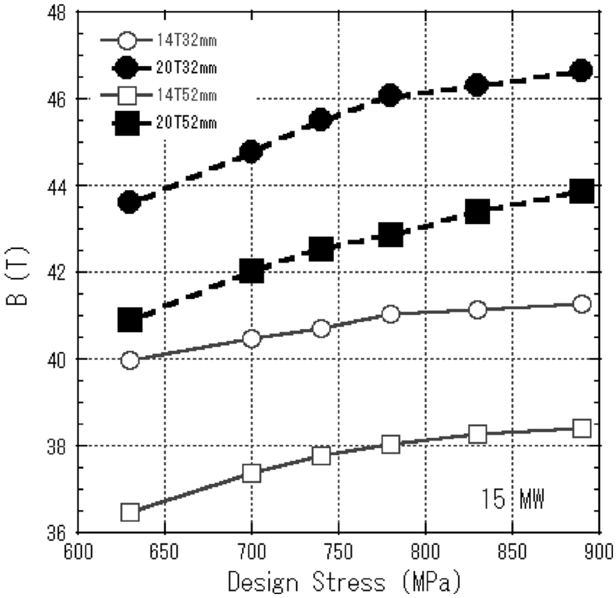

Fig. 3. Calculated result of the achieved magnetic field in the tentative hybrid magnets under the restrictions described in the text. The outer diameter of the resistive insert magnets is 340 mm, and that of the RT bore is 32 mm (circle) or 52 mm (square). The resistive inserts are operated at a power of about 15 MW under backup fields of 14.02 T (open symbols) or 20 T (filled symbols). The materials used for the Bitter disks of the coils, except for the outer coil in this insert magnet, have conductivity from approximately 74 to 75%IACS. The lines are guides for the eye.

B. 32 mm RT bore HM

The existing HM in the TML generates 37.9 T under a backup field of 14.02 T with an operating power of 13.35 MW for the resistive insert [1]. By increasing the operating power for the resistive insert up to 15 MW and using a traditional Cu-Ag plate, a center field of 40 T is attainable in the 32 mm RT bore, although a new resistive insert needs to be manufactured. The values of the magnetic field additionally generated by the resistive insert under the backup field of the SM, which are expected to increase as a result of the increase of the maximum design stress in the Bitter disk from 630 MPa to 890 MPa, reached from 26 T to 27.3 T in the 14.02 T SM and from 23.6 T to 26.5 T in the 20 T SM, as calculated for the 15 MW operation. A field of about 45 T is expected to be achieved by combining the 20 T SM and the strong plate for the Bitter disk with an average UTS of 1000 MPa (the maximum design stress is 700 MPa). The generation of a magnetic field of 46.3 T is expected by the 20 T SM and Bitter coils made of a plate with a UTS of 1200 MPa. This calculation result shows that the average UTS of 1140 MP is strong enough for the resistive insert to exceed 46 T under a 20 T 400 mm SM.

IV. Resistive Insert Specifications

A. For a 43 T HM With 52 mm RT Bore

A maximum design stress of around 830 MPa is selected in this tentative design of the resistive insert to generate 43.4 T in the 15 MW operation under a backup magnetic field of 20 T. This resistive insert corresponds to the filled square symbol at the design stress of 830 MPa in Fig. 3. The average UTS of the plate corresponding to the definition in this study is 1186 MPa.

TABLE II
Parameters of the 52 mm 43 T Hybrid Insert

Coil	A	B	C
Inner radius (mm)	29.0	80.5	127.5
Outer radius (mm)	78.5	126.5	170.0
Height (mm)	241.9	367.2	408.0
Field (T)	11.95	8.70	2.77
Material	---	---	Cu-Cr
Stress (MPa)	826	830	303
Power (MW)	5.38	8.30	1.40
Voltage (V)	154.1	278.7	278.7
Current (kA)	34.94	29.88	5.06
Jmax (A/mm2)	485.5	305.2	99.0
Max. temp. (˚C)	98	98	47
Number of holes	224	288	240
Tie rods	16	24	24
Disks/turn	8	8	4
	16	16	8
Turns (main)	64	61	176
(end region total)	4	22	30
Disc thickness. (mm)	0.4	0.41	0.4

TABLE III
Parameters of the 32 mm 46 T Hybrid Insert

Coil	A1	A2	B	C
Inner radius (mm)	19.0	39.0	69.5	127.5
Outer radius (mm)	38.0	67.0	126.5	170.0
Height (mm)	273.4	245.0	429.6	454.0
Field (T)	7.23	6.86	9.50	2.73
Material	---	---	---	Cu-Cr
Stress (MPa)	834	834	766	291
Power (MW)	2.54	2.71	8.48	1.35
Voltage (V)	151.3	151.3	281.5	281.5
Current (kA)	16.96	18.01	30.17	4.80
Jmax (A/mm2)	699	410	265	96
Max. temp. (˚C)	80	69	65	54
Number of holes	128	128	336	240
Tie rods	0	16	24	24
Disks/turn	8	8	8	4
	16	16	16	8
Turns (main)	62	52	78	183
(end region total)	16	16	22	40
Disc thickness (mm)	0.34	0.34	0.41	0.4

The specifications of the resistive insert for the 43.4 T HM are listed in Table II. The coil layout and connection method are almost the same as those in Fig. 2, though the widths of the cooling holes were increased.

B. For a 46 T HM With 32 mm RT Bore

This resistive insert corresponds to the filled circle symbol at a design stress of 830 MPa in Fig. 3. This resistive insert was also based on the success of the development of a plate with an average UTS exceeding 1186 MPa to make the Bitter disks for the inner coils. For the middle coil, the design stress restriction is 766 MPa. New materials are necessary for both coils. The specifications of the resistive insert for the 46.3 T HM are presented in Table III.

The hole layout of the Bitter disks follows that of the Florida Bitter, and the innermost coil of the three-layered multi-Bitter coil is divided into two concentric coils. The inner coil of the innermost coil unit is tightened by shared tie rods with this innermost coil unit. This fundamental composition is almost the same as that in the schematic sectional view in a previous report

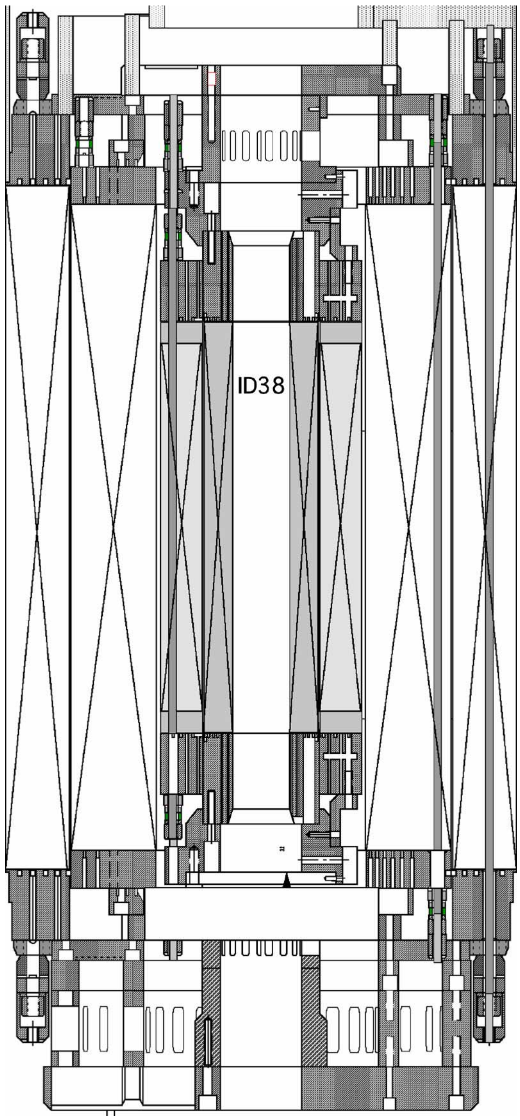

Fig. 4. Coil layout of the resistive insert for the 32 mm RT bore 46.3 T hybrid magnet. The outer diameter is 340 mm. The two outer coils are connected in parallel. The innermost coil is connected in series to these two outer coils. This magnet is built in a pipe with an inner diameter of 365 mm and an outer diameter 395 mm. This pipe is located in the 400 mm RT bore of the 20 T SM outsert.

[1] except for the method of connecting coils A1 and A2. The cross-sectional layout of the coils is illustrated in Fig. 4.

V. Conclusion

We conducted a parameter survey to clarify the strength requirement for a Bitter disk of a resistive insert for a 20 T SM outsert maintaining the maximum DC power supply for the resistive insert up to 15 MW. The results indicate that an average UTS of 1186 MPa at room temperature is needed for the Bitter disk of this resistive insert to generate 43.4 T in a 52 mm RT bore and 46.3 T in a 32 mm RT bore, although the increasing forces at the coil end must be taken into consideration. This strength is much greater than that of the existing Cu-Ag plate. It would be necessary to improve the strength of the Cu-Ag plate up to this value or develop new materials to realize a 45 T HM in which the operating power of the resistive insert is 15 MW. Conductivity above 73% IACS would also be required.

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